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**THERMAL EMBRITTLEMENT OF STEEL FOR  
175-MM GUN TUBES**

**Technical Report by**

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ABSTRACT

Sections of two 175-mm M113 gun tubes were utilized to study the development of both reversible and irreversible temper brittleness in 3 percent nickel-chromium gun steel. Relative material toughness indicated by the 100 percent fibrous transition temperature was determined on numerous groups of specimens tempered between 900 and 1200 F for various times.

A tempering range of 1075 to 1100 F produced optimum toughness at the required 160 to 180 ksi yield strength for tempering times consistent with the section size of forgings for 175-mm tubes. Lower tempering temperatures resulted in a greater degree of reversible temper brittleness, particularly 1000 F, which produced maximum embrittlement within the limits studied. Regression was observed at 1050 F after prolonged tempering.

Both the kinetics of temper brittleness and the effects of composition on the degree of embrittlement are discussed in terms of numerous determinations available in the literature. The indirect effect of temperability as well as the dual role of some elements such as molybdenum and vanadium are described. Previous limited results from a cursory study performed by a producer are explained in terms of embrittlement and regression.

The acute necessity of impact tests for the quality assurance of forgings having the required yield strength is demonstrated.

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## INTRODUCTION

A comprehensive metallurgical study<sup>1</sup> of the 175-mm M113 gun tube production revealed serious deficiencies in material toughness. Although other factors such as prior austenitic grain size sometimes contributed to this deficiency, diversified tempering treatments appeared to have a pronounced effect on the notch toughness of the materials. The 100% fibrous transition temperature, which indicates the relative toughness of these gun tubes, varied from about 0 to 150 C. This variation in the relative degree of toughness was independent of both the yield and the ultimate tensile strengths. Information indicated that tempering was generally performed at temperatures conducive to temper brittleness. In many cases development of this brittleness was enhanced either by prolonged or accumulative tempering cycles. The aim of this investigation was to determine the susceptibility of 3% Ni-Cr gun steel to temper brittleness. It was preferred to utilize a procedure which would provide direct guidance for the production heat treatment of forgings for 175-mm tubes with optimum material toughness. To accomplish this purpose a study of the relative toughness resulting from various combinations of time and tempering temperature was made. The 100 percent fibrous transition temperature was utilized to evaluate material toughness resulting from the various tempering cycles.

## PROCEDURE

Sections cut from production tubes 113 and 967 were utilized as material for this study. This choice of gun tubes was based on several factors, namely: availability; comparable compositions; and significant differences in the toughness. The sections were annealed at 1650 F, then machined into oversize longitudinal specimen blanks, which were heat treated as follows: 1650 F, 1 hour, air cooled; 1550 F, 1 hour, oil quenched. Groups of these blanks were then tempered between 900 and 1200 F for times which varied from a fraction of an hour to 192 hours, followed by water quenching. The blanks were then finished machined into 0.394-inch square Charpy V-notch impact specimens. Four Rockwell C hardness measurements were made on each specimen and the values were averaged for each group representing a specific tempering treatment. The impact specimens were tested over a range of temperatures between -196 and +200 C (-320 and +290 F) on a pendulum-type machine having a capacity of 215 foot-pounds and a striking velocity of 16.8 feet per second. The percent fibrous fracture of each specimen was determined according to the ASTM method<sup>2</sup> and was plotted as a function of testing temperature to obtain the transition temperature for both materials resulting from each tempering treatment.

## RESULTS AND DISCUSSION

The chemical compositions of these materials were previously determined<sup>1</sup> and are listed in Table I. The normalizing and hardening treatments produced a finer prior austenitic grain size than the previous production treatment.

The grain size was determined to be ASTM 11 for material from tube 113 and ASTM 10 for material from tube 967. Originally the grain sizes had been 8 and 5 to 7, respectively.<sup>1</sup>

Table I. CHEMICAL COMPOSITION

Wt %			ppm		
Element	Tube 113	Tube 967	Element	Tube 113	Tube 967
C	0.33	0.33	As	102	92
Mn	0.28	0.38	Sb	22	30
Si	0.56	0.53	Sn	73	87
Ni	3.53	3.36	O	52	74
Cr	0.66	0.73	H	0.2	0.3
Mo	0.81	0.80	N	34	57
P	0.006	0.005			
S	0.007	0.006			
V	0.14	0.09			

The 100 percent fibrous transition temperatures and average  $R_C$  hardness values for the various tempering treatments are compiled in Table II for the material from tubes 113 and 967. Also included are the values obtained with the Holloman-Jaffe<sup>3</sup> tempering parameter  $M$ :

$$M = T (C + \log t)$$

where  $T$  = temperature in degrees Rankin  
 $C$  = 19.3 for 0.33% (weight) carbon  
 $t$  = time in hours

These values are included as a convenient means of comparing the degree of tempering resulting from various combinations of time and temperature. After any tempering treatment the resulting material toughness would depend on two possible factors which exert opposite effects on toughness: (1) the inherent increase in toughness of the specific composition resulting solely from the respective tempering reaction; and (2) the degree of any thermal embrittlement that may develop during the same tempering treatment.

#### Irreversible Temper Brittleness

Tempering temperatures of 1150 and 1200 F would not be feasible for production heat treatment of 175-mm gun tubes due to both the section size and the required yield strength (160 to 180 ksi). These tempering temperatures were included, however, for two purposes. Gun tubes of different caliber and design, requiring lower strength levels, could be tempered at these temperatures. The toughness of a steel tempered at 1150 and 1200 F could be dependent on any irreversible or "upper nose" temper brittleness<sup>4</sup> that may develop during tempering. This form of thermal embrittlement has been determined by Clancy and Norton<sup>5</sup> to be due to the changing morphology and size of ferrite grains concurrent with the growth of carbides with increasing time at these or higher subcritical temperatures. The transition

Table II. TRANSITION TEMPERATURE AND HARDNESS DATA

Tube 113									
Tempering		Mx10 <sup>-3</sup> *	Trans. Temp. (deg C)	Hard- ness R <sub>c</sub>	Tempering		Mx10 <sup>-3</sup> *	Trans. Temp. (deg C)	Hard- ness R <sub>c</sub>
Temp.	Time (hr)				Temp.	Time (hr)			
1200 F (650 C)	1	32.04	-40	37.8	1050 F (580 C)	0.25	28.23	10	43.1
	2	32.54	-60	35.1		0.50	28.69	10	43.4
	4	33.04	-65	31.9		0.75	28.95	10	43.5
	8	33.54	-75	28.4		1	29.14	15	43.4
	16	34.04	-65	26.8		2	29.60	5	43.7
	32	34.54	-60	24.6		4	30.05	0	43.6
	64	35.04	-15	21.4		8	30.51	0	42.8
	88	35.23	-10	19.7		12	30.77	10	42.8
	96	35.33	-10	20.8		16	30.96	30	42.7
						32	31.42	40	41.4
1150 F (620 C)	0.5	30.58	10	43.0	1000 F (540 C)	48	31.68	40	40.1
	1	31.07	0	42.5		64	31.87	30	39.0
	2	31.56	-5	42.8		96	32.14	-20	35.0
	4	32.04	-15	39.2		192	32.59	-45	33.5
	8	32.53	-55	34.7		0.5	27.74	10	43.8
	12	32.81	-60	33.8		1	28.18	10	44.4
	12	32.81	-60	33.2		2	28.62	20	44.7
	16	33.01	-60	32.1		4	29.06	10	44.5
	24	33.29	-55	31.1		6	29.31	5	44.8
	48	33.78	-50	28.0		6	29.31	10	44.5
1100 F (595 C)	64	33.98	-55	29.6	950 F (510 C)	8	29.50	5	44.8
	88	34.17	-55	25.3		12	29.75	10	45.1
	96	34.26	-45	24.7		16	29.94	25	44.7
	192	34.75	-20	22.8		64	30.81	30	46.0
	0.5	29.64	10	43.6		96	31.07	40	42.8
	1	30.11	0	43.9		192	31.51	75	42.6
	2	30.58	10	43.4		0.5	26.79	30	44.9
	4	31.05	20	44.6		1	27.21	30	45.2
	8	31.52	-5	40.9		2	27.64	30	45.1
	12	31.79	-15	39.0		4	28.06	30	45.6
1075 F (580 C)	12	31.79	-15	39.0	900 F (485 C)	16	28.91	40	45.8
	16	32.00	-30	38.1		20	29.05	30	46.2
	24	32.26	-35	37.7		24	29.16	25	44.7
	32	32.46	-45	34.6		32	29.34	40	45.0
	48	32.73	-40	34.6		64	29.76	50	46.9
	64	32.93	-40	33.6		192	30.43	60	44.9
	192	33.67	-45	27.3		4	27.07	40	45.7
	0.5	29.16	-5	44.2		16	27.89	35	45.9
	1	29.63	-5	44.1		48	28.53	25	45.0
	4	30.55	5	43.4		96	28.94	40	45.5
	8	31.01	-5	42.4		144	29.18	40	45.8
	12	31.28	10	42.1		192	29.35	40	45.6
	16	31.47	5	41.4	*M = deg R ( C + log t ) where C = 19.3 for 0.33% carbon t = tempering time in hours				
	32	31.94	-25	39.8					
	64	32.40	-40	34.8					
	88	32.58	-45	31.9					
	96	32.67	-55	30.9					
	192	33.13	-55	29.0					

Table II. TRANSITION TEMPERATURE AND HARDNESS DATA (cont.)

Tube 967									
Tempering		Mx10 <sup>-3*</sup>	Trans. Temp. (deg C)	Hard- ness R <sub>c</sub>	Tempering		Mx10 <sup>-3*</sup>	Trans. Temp. (deg C)	Hard- ness R <sub>c</sub>
Temp.	Time (hr)				Temp.	Time (hr)			
1200 F (650 C)	1	32.04	-60	37.1	1050 F (565 C)	0.25	28.23	10	43.1
	2	32.54	-65	34.5		0.50	28.69	10	43.4
	4	33.04	-75	31.5		0.75	28.95	10	43.5
	8	33.54	-70	27.6		1.0	29.14	15	43.4
	16	34.04	-65	26.2		2	29.60	5	43.7
	32	34.54	-45	23.7		4	30.05	0	43.6
	64	35.04	10	20.9		8	30.51	0	42.8
	88	35.23	20	19.9		12	30.77	10	42.8
	96	35.33	30	19.9		16	30.96	30	42.7
						32	31.42	40	41.4
1150 F (620 C)	0.5	30.59	0	42.1	1000 F (540 C)	0.5	27.74	25	43.3
	1	31.07	-5	41.8		1	28.18	15	43.9
	2	31.56	-10	40.0		2	28.62	10	44.7
	4	32.04	-20	38.1		3	28.87	10	43.7
	8	32.53	-60	33.3		6	29.31	5	45.0
	12	32.81	-60	33.1		8	29.50	15	45.1
	24	33.29	-55	29.8		16	29.94	25	43.9
	48	33.78	-55	28.0		48	30.63	30	43.5
	64	33.98	-45	25.9		64	30.81	25	45.0
	192	34.75	-20	22.4		96	31.07	55	41.8
1100 F (595 C)	0.5	29.64	20	42.9	950 F (510 C)	0.5	26.79	30	44.0
	1	30.11	5	42.7		1	27.71	25	44.6
	2	30.58	5	42.3		2	27.64	25	44.9
	4	31.05	-10	43.5		4	28.06	20	44.9
	8	31.52	-10	40.0		16	28.91	30	45.3
	12	31.79	-15	38.0		20	29.05	30	45.3
	16	32.00	-25	35.6		24	29.16	25	44.1
	24	32.26	-25	36.7		32	29.34	30	44.4
	32	32.46	-45	34.6		64	29.76	45	44.5
	48	32.73	-50	34.1		96	30.01	30	44.5
1075 F (580 C)	64	32.93	-45	32.9	900 F (485 C)	192	30.43	40	43.7
	192	33.67	-55	26.4		4	27.07	35	44.9
	0.5	29.16	5	43.5		16	27.89	40	45.3
	1	29.63	10	43.2		48	28.53	45	44.4
	4	30.55	5	42.4		96	28.94	40	44.8
	8	31.01	10	41.4		144	29.18	40	44.5
	12	31.28	10	41.4		192	29.35	50	44.5
	16	31.47	5	40.5					
	32	31.94	-30	36.8					
	64	32.40	-40	33.9					
	88	32.58	-45	31.0					
	96	32.67	-60	30.7					
	192	33.13	-60	28.0					

\*M = deg R (C + log t)  
 where C = 19.3 for 0.33% carbon  
 t = tempering time in hours



temperatures obtained by tempering at 1150 and 1200 F are included in Table II and are illustrated in Figure 1. The results indicate that at 1150 F, the temperability of this steel has a marked influence on the resulting material toughness for tempering times less than 8 hours. The relatively slow rate of embrittlement at this temperature exerts little effect on toughness except at prolonged times of 2 days or more. At 1200 F the increase in the rates of both the tempering and the embrittling reactions reduce the time required to achieve optimum material toughness. The results also indicate that section size should control the choice of the specific tempering temperature as well as the time in this temperature range.

### Toughness and Tempering Temperature

Transition temperatures resulting from various tempering treatments between 900 and 1100 F are listed in Table II and illustrated in Figure 2. The scatter in the data is attributed primarily to the residual dendritic macrostructure.<sup>1</sup>

Modified requirements<sup>6</sup> for the 175-mm gun tubes stipulate a yield strength of 160 to 180 ksi. This requirement necessitates a Rockwell hardness of approximately 39 to 44. Considering both this hardness range and the tempering time required based on section size, the data indicate a tempering range of 1075 to 1100 F would produce optimum toughness. Higher temperatures do not appear to be feasible due to the mass of these tubes. Lower temperatures necessitate increased tempering times to obtain the desired hardness. The required times at these lower temperatures would be deleterious due to the development of reversible temper brittleness indicated by higher transition temperatures (Table II). This type of brittleness is known to develop within - but not necessarily throughout - this range of temperatures (900 to 1100 F). A study of the kinetics of temper brittleness<sup>7</sup> indicates the rate of embrittlement is most rapid in the vicinity of 1000 F and diminishes appreciably at both higher and lower temperatures. Except for prolonged times (days), neither reversible nor irreversible temper brittleness develops in the vicinity of 1100 F. The choice of tempering temperature controls material toughness for a wide range of ultimate tensile strengths. This is illustrated in Figure 3 where the transition temperatures derived from the curves of Figures 1 and 2 (at constant arbitrary tempering times) are plotted as a function of the tempering parameter. In addition, the range of hardness values obtained from all tempering treatments is included. Figures 3a and 3b vividly illustrate that at any hardness level the relative toughness is very dependent on the tempering temperature utilized. This behavior depicts the potency of both reversible and irreversible temper brittleness. Although the degree of embrittlement may differ due to composition the general behavior of both materials with respect to toughness was similar for each respective tempering treatment. The results (Figures 1 to 3) can be generalized according to tempering temperatures.

At both 900 and 950 F there is a constant small increase in transition temperatures with increased tempering times within the limit studied (about 200 hours). Slightly lower transition temperatures are obtained at 1000 F

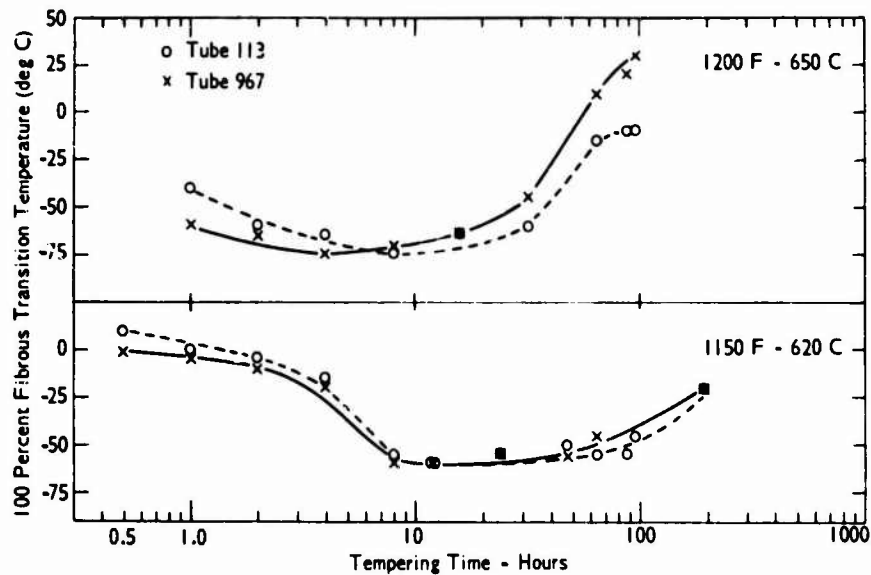


Figure 1. TRANSITION TEMPERATURE VERSUS TEMPERING TIME

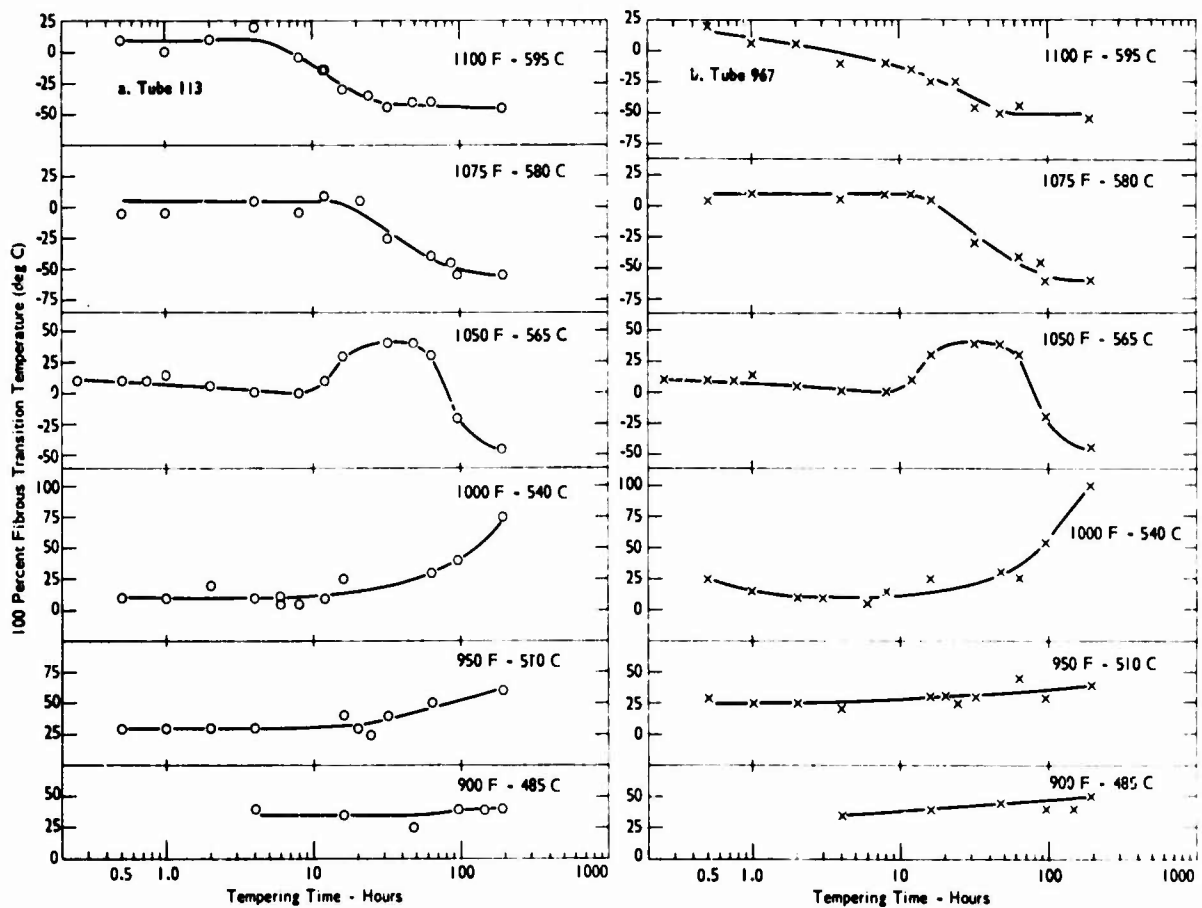


Figure 2. TRANSITION TEMPERATURE VERSUS TEMPERING TREATMENTS

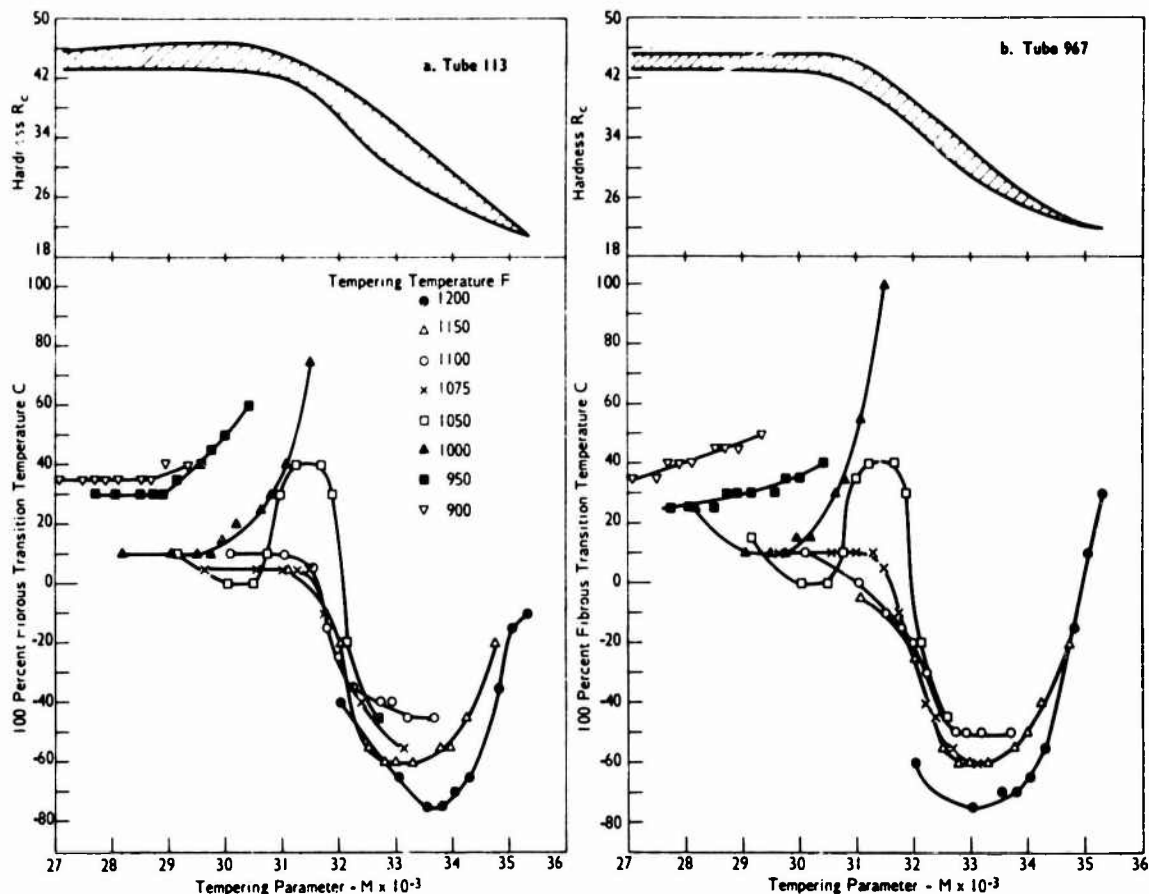


Figure 3. TRANSITION TEMPERATURE AND HARDNESS VERSUS TEMPERING PARAMETER

for times less than 10 hours. At longer times there is a marked increase in transition temperatures with increasing time. Prolonged tempering resulting in embrittlement would be necessary at this temperature to achieve a hardness of  $R_c$  39 to 44. As expected, this tempering temperature produced the highest transition temperatures obtained in this investigation.

At 1050 F a significant increase in transition temperatures results from tempering times of 8 to 48 hours. For longer tempering times there is a rapid regression to considerably lower transition temperatures. In Figure 2 the curves illustrating the data for 1050 F are analogous to curves depicting "overaging" in nonferrous alloys. Somewhat similar behavior was reported by Vidal<sup>8</sup> for chromium steel tempered at 1068 F (575 C). For this chromium steel regression occurred after only 2 hours. The shortness of time was most likely due to Vidal's procedure which included an initial temper at 1200 F (650 C) prior to the 1068 F treatment. The behavior of gun steel with respect to toughness when tempered at 1050 F explains the results obtained and reported by Bethlehem Steel Corporation.<sup>9</sup> In that study starting material was obtained from production tubes tempered at 1050 F. Subsequent procedure consisted of retempering. Retempering at lower temperatures increased transition

temperatures but retempering at higher temperatures decreased transition temperatures. The initial tempering time at 1050 F would be in the 8-to-48-hour time bracket due to the section size and required yield strength. This combination of time and temperature for this type of steel would result in embrittlement (Figures 2 and 3). Retempering at lower temperatures would enhance this embrittlement. Retempering at higher temperatures would expedite the regression of this reversible form of temper brittleness.

#### Temperability and Reversible Temper Brittleness

Within limits, the temperability of this type of steel as well as the choice of tempering temperature can enhance the degree of temper brittleness. In general, there is a dual effect on the degree of embrittlement with decreasing tempering temperatures. Due to the kinetics of the reaction there is an increase in the rate of embrittlement as the tempering temperature approaches 1000 F.<sup>4,7</sup> The marked increase in tempering time necessary to achieve the required hardness also increases the amount of temper brittleness. This is illustrated below by data extracted from Table II.

Tube 113						
Tempering (deg F)	Temperature (deg C)	Time (Hours)	Hardness R <sub>C</sub>	Mx10 <sup>-3</sup>	Transition (deg F)	Temperature (deg C)
1150	620	1	42.5	31.07	32	0
1075	580	8	42.4	31.01	41	5
1050	565	16	42.7	30.96	86	30
1050	565	32	41.4	31.42	104	40
1000	540	96	42.8	31.07	104	40
1000	540	192	42.6	31.51	167	75
Tube 967						
1150	620	1	41.8	31.07	23	-5
1075	580	8	41.4	31.01	50	10
1050	565	16	42.7	30.96	86	30
1050	565	32	41.4	31.52	104	40
1000	540	96	41.8	31.07	122	55
1000	540	192	41.4	31.51	212	100

#### Anisothermal Embrittlement

Another factor which can influence the toughness of heavy forgings is the temper brittleness that may develop during cooling from the temper. A determination of the susceptibility of this type of steel under anisothermal conditions was made with specimens from tube 967. These specimens were tempered for 1 hour at 1050 F. Each group was furnace cooled at one of three controlled cooling rates to the vicinity of 400 F, then water quenched. Previous data indicated that water quenching after 1 hour at this temperature would result in a transition temperature of about 10 degrees C (Figure 2). Thus, any increase in transition temperature above 10 degrees C could be

attributed to the cooling rate. The results obtained are listed together with the difference in transition temperatures obtained by furnace cooling after 1 hour at 1050 F.

Cooling Rate deg F/hour	Transition Temperature		Difference*	
	deg C	deg F	deg C	deg F
10	90	194	80	144
30	30	86	20	36
45	15	59	5	9

\*10 deg C obtained by water quench

These results indicate that there is a critical cooling rate for this steel which must be achieved to avoid embrittlement under anisothermal conditions. The data indicate this rate to be about 45 F (25 C) per hour. Thus avoidance of reversible temper brittleness in forgings for large caliber tubes at the required strength necessitates dual precautions, namely a sufficiently high tempering temperature; and a sufficiently rapid cooling rate from the temper.

#### Temper Brittleness

The results obtained in this study confirm the findings of an earlier metallurgical investigation with respect to temper brittleness. Similar confirmation also applies to the findings of Davidson et al.<sup>10</sup> of Watervliet Arsenal as well as Large, et al.<sup>11</sup> of ManLabs Inc.

This type of steel has been associated with temper brittleness for half a century. A quarter century ago the detrimental effects of small amounts of tin on this same type of steel were reported by Bolsover and Barraclough.<sup>12</sup> These investigators also noted the beneficial effects of 0.25% molybdenum. Later the effects of arsenic and antimony on the development of temper brittleness were studied by Austin, et al.<sup>13</sup> In 1959 Steven and Balajiva<sup>14</sup> reported the influence of many minor elements on the embrittlement of this gun steel. These investigators demonstrated that the development of temper brittleness required residual elements such as phosphorus, antimony, arsenic, and tin. In the meantime, Powers<sup>15,16</sup> made comprehensive studies of the influence of molybdenum, tungsten, and vanadium on the development of temper brittleness in a 1% chromium-1% manganese steel. These elements were found to have a complex influence on the embrittlement of this steel. Individually, 1/2% molybdenum or 1% tungsten strongly inhibited embrittlement but the effectiveness of both elements diminished with increased amounts.<sup>15</sup> In contrast, these elements are embrittling when present in amounts equal to or greater than 3/4% molybdenum or 1% tungsten.<sup>16</sup> Vanadium in the absence of molybdenum was found to embrittle intensely.<sup>16</sup> Additions of both molybdenum and vanadium in amounts of 1/2% or more greatly reduced the susceptibility of the chromium-manganese steel.<sup>16</sup> Powers concluded that the susceptibility of chromium-manganese steel depended on the interaction of these atoms.

Since 1925 numerous reports in the literature have associated the degree of embrittlement with concentrations of major alloying elements, particularly chromium and manganese. Recently Low et al.<sup>17</sup> demonstrated, by a very comprehensive study, that although temper brittleness results from minor elements, the severity of the embrittlement depended on the interaction of the major alloying elements. For controlled amounts of minor elements nickel-chromium steel was found to be very susceptible to reversible temper brittleness. This steel had much greater susceptibility than either a chromium or a nickel steel. The degree of embrittlement which may develop in a steel depends, therefore, on two factors: (1) the composition with its complex interactions of both major and minor elements; and (2) the thermal treatments including the rate of cooling from the temper. The effects of temperability must also be considered. Elements such as molybdenum and vanadium which are known to affect the susceptibility of a steel to temper brittleness, also retard the tempering reaction.<sup>3</sup> As the degree of embrittlement is dependent on both time and temperature these elements exert a dual influence on material toughness.

Various mechanisms have been proposed to explain the phenomenon of temper brittleness. Early theories suggested a precipitate at the grain boundaries. More recent proposals suggest segregation. Unfortunately none of these explanations have been substantiated with adequate experimental evidence.

### Composition and Toughness

Recently Vishnevsky and Steigerwald<sup>18</sup> made a study of the effects of alloying elements on the toughness of this gun steel at a yield strength of 160 to 180 ksi. They utilized vacuum-melted heats representing individual quantitative changes in composition. Two criteria were utilized to evaluate material toughness - transition temperatures obtained from both fracture toughness tests and Charpy impact tests. Both criteria confirmed the deleterious effects of increasing amounts of carbon, manganese, silicon, chromium, and molybdenum on material toughness. The effects of vanadium on the transition temperature of this steel were complex. Better toughness was obtained by the addition of 0.28% V or the small amount (~0.01%) normally added for grain refinement, than by the intermediate amount of 0.1%.

### Quality Assurance

Vishnevsky and Steigerwald<sup>18</sup> reported that relative changes in transition temperature of their notch bend specimens corresponded with shifts in Charpy impact transition temperature. The criterion utilized for their bend tests approximated the change in the fracture mode from plane strain to plane stress. Carr, Nunes, and Larson<sup>19</sup> studied the effects of temper brittleness on mechanical properties as well as on crack propagation in terms of fracture surface topography on 3140 steel. Both of these investigations justify again the requirement for impact tests for quality assurance. For the required hardness the feasibility of a single testing temperature of -40 F to determine acceptability of forgings having sufficient strength and ductility is demonstrated by selected data.

### IMPACT TESTS AT -40 F

Tempering Temperature		Hardness R <sub>c</sub>	Impact Energy ft-lb	Fibrous Fracture (%)
(deg F)	(deg C)			
Tube 113				
1150	620	42.5	28.3	75
1075	580	42.4	26.5	70
1050	565	42.7	25.8	45
1000	540	42.6	15.8	20
Tube 967				
1150	620	41.8	31.8	60
1075	580	41.4	25.4	55
1050	565	41.4	21.1	45
1000	540	41.4	17.1	25

Both the impact energy and the percent fibrous fracture indicate the deleterious effects of temper brittleness. In addition, these data emphasize the acute necessity of Charpy impact tests for the quality assurance of these gun tubes.

### SUMMARY

1. Determinations were made of the relative toughness of 3½ nickel-chromium steel resulting from tempering at various temperatures between 900 and 1200 F for various times to about 200 hours.
2. This steel was susceptible to both reversible and irreversible temper brittleness.
3. A tempering range of 1075 to 1100 F produced optimum toughness at 160 to 180 ksi yield strength for tempering times consistent with the section size of forgings for 175-mm tubes. Other temperature ranges may be preferable for different yield strengths and different size tubes.
4. Reversible temper brittleness can develop in this steel during slow cooling from the temper. The degree of embrittlement is dependent on the cooling rate. A critical rate of about 45 F per hour through the embrittling range must be achieved to avoid anisothermal embrittlement.
5. Regression was observed at 1050 F for tempering times in excess of 48 hours.
6. The temperability of this steel is insufficient to offset the deleterious effects of the embrittling reactions encountered in certain temperature ranges.
7. Molybdenum and vanadium appear to have a dual role with respects to material toughness. In addition to any interactions with other elements affecting embrittlement, these elements have a significant effect on temperability.

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13. ABSTRACT - Sections of two 175-mm M113 gun tubes were utilized to study the development of both reversible and irreversible temper brittleness in 3 percent nickel-chromium gun steel. Relative material toughness indicated by the 100 percent fibrous transition temperature was determined on numerous groups of specimens tempered between 900 and 1200 F for various times.  A tempering range of 1075. to 1100 F produced optimum toughness at the required 160 to 180 ksi yield strength for tempering times consistent with the section size of forgings for 175-mm tubes. Lower tempering temperatures resulted in a greater degree of reversible temper brittleness, particularly 1000 F, which produced maximum embrittlement within the limits studied. Regression was observed at 1050 F after prolonged tempering.  Both the kinetics of temper brittleness and the effects of composition on the degree of embrittlement are discussed in terms of numerous determinations available in the literature. The indirect effect of temperability as well as the dual role of some elements such as molybdenum and vanadium are described. Previous limited results from a cursory study performed by a producer are explained in terms of embrittlement and regression.  The acute necessity of impact tests for the quality assurance of forgings having the required yield strength is demonstrated. (Authors)		

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